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BJØRN KJÆRNSLI

Test Results

Oslo Subway

Norwegian Contribution No. 6

Trondheim 1960

Also published in the Proceedings of the Brussels Conference 1958
on Earth Pressure Problems

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SUMMARY

Oslo Subway, which will pass through soft, normally consolidated clay, is partly built in open excavation. At the very first stage of this excavation work, which has been carried out between strutted sheet piles, testing equipment has been installed for the purpose of measuring earth pressure on the sheet piles, stresses in the sheet piles, strut loads, pore pressure and settlements. This article gives the results obtained up to March, 1958.

The results of the measurements of the earth pressure on the sheet piles, so far obtained, show that the earth pressure is not distributed in accordance with the classical theory. For the stage of the conctruction when the sheet piles are strutted at one level only, the measured earth pressure distribution seems to be fairly well in accordance with the theory of Brinch Hansen, and the earth pressure measured is fairly well enclosed by the empirical diagram by R. Peck.

1. INTRODUCTION

Foundation engineers may, if in nothing else, agree with the claim that increasing knowledge in this fields depends to a great extent upon the experience gained through small or full scale tests, and on observations on pratical jobs. In consulting work, one can agree, forthermore, that it is often very difficult to give an accurate answer to questions concerning earth pressure.

In connection with the design of Oslo Subway, the engineers at the Norwegian Geotechnical Institute, due to their lack of knowledge, convinced the Authority of Oslo that any observations which could be made would lead to better understanding, and possibly to lighter dimensions of the further design.

The job concerns building that part of the Oslo Subway which is to pass through deep deposists of soft, normally consolidated, silty clay. The subway, which will be constructed at small depth, is to be built partly in open excavations between strutted sheet piles, and partly under air pressure. The value of observations of any kind depends upon the measuring equipment, and its installation. K. Øyen has presented a paper describing the equipment for the observations so far carried out on the first test section of Oslo Subway, and I. Johannessen has described the installation. The latter paper also describes the

condition at the test section. An acquaintance of the above mentioned papers in necessary for a full understanding of the following paper.

The excavation concerned was started in August 1957 and is at the time of writing not yet completed. The excavation is carried out between sheet piles, Belval Z IVN-50 driven down approximately 2" into the rock, which may be described as a bituminous shale of Cambrian age.

2. TEST RESULTS

To the knowledge of the author, the determination of the earth pressure distribution on a strutted sheet pile in clay by means of direct measurement, has not been published previously. In the following, therefore, the results of these measurements are given priority. As may be seen from the paper by I. Johannessen (1958), the eleven earth pressure cells are placed on two test piles situated opposite each other in the excavation. The vertical distance between the cells on each pile is 2,0 meters. Considering both test piles together, the cells are staggered vertically with approximately 1,0 meter difference in level. All cells are situated in such a way that they register the earth pressure on the active side of the wall.

On Fig. 1 the registered earth pressures on all cells are given at different dates. In the same figure, the pore pressure is shown measured as the stand pipe level in open tubes with piezometer points at different depths and at a distance of approximately 0,5 m from the sheet piles. Furthermore, curves showing the measured strut loads, and the average daily temperature are drawn. At the bottom of the figure, the stage of construction is illustrated, and the dates for the pile driving, placing of struts, and depth of excavation are noted.

In Figs 2 and 3 is shown a profile through the test section. The earth pressures measured on both piles are plotted on the right hand side and the pore pressure on the left. Furthermore, the drop in level of zero pore pressure (ground water level) and the settlements of the surface are illustrated.

The earth pressure and the pore pressure immediately after driving the test piles from the excavated level + 0,3 are given in Fig. 2. The earth pressure at this stage may be said to be distributed nearly hydrostatically. The maximum earth pressure at level -6,0 is equal to the total overburden pressure.

The pore pressure registered immediately after driving is very irregular and probably does not represent the pore pressure at the face of the test piles. This pore pressure may rather be assumed to be equal to the overburden pressure reckoned from level + 0,3.

Until the excavation from level + 0,3 begins, the earth pressure as well as the pore pressure decreases as a result of the consolidation which takes place, Fig. 1. The registered increased pressure at level -0,7 is probably due to the weight of a driving hammer (7t) working at level + 0,3 in the period between 17.—29. October, 1957. With excavation below level + 0,3 however, the earth pressure does not change primarily as a result of consolidation, but is mainly due to the deflection of the sheet pile.

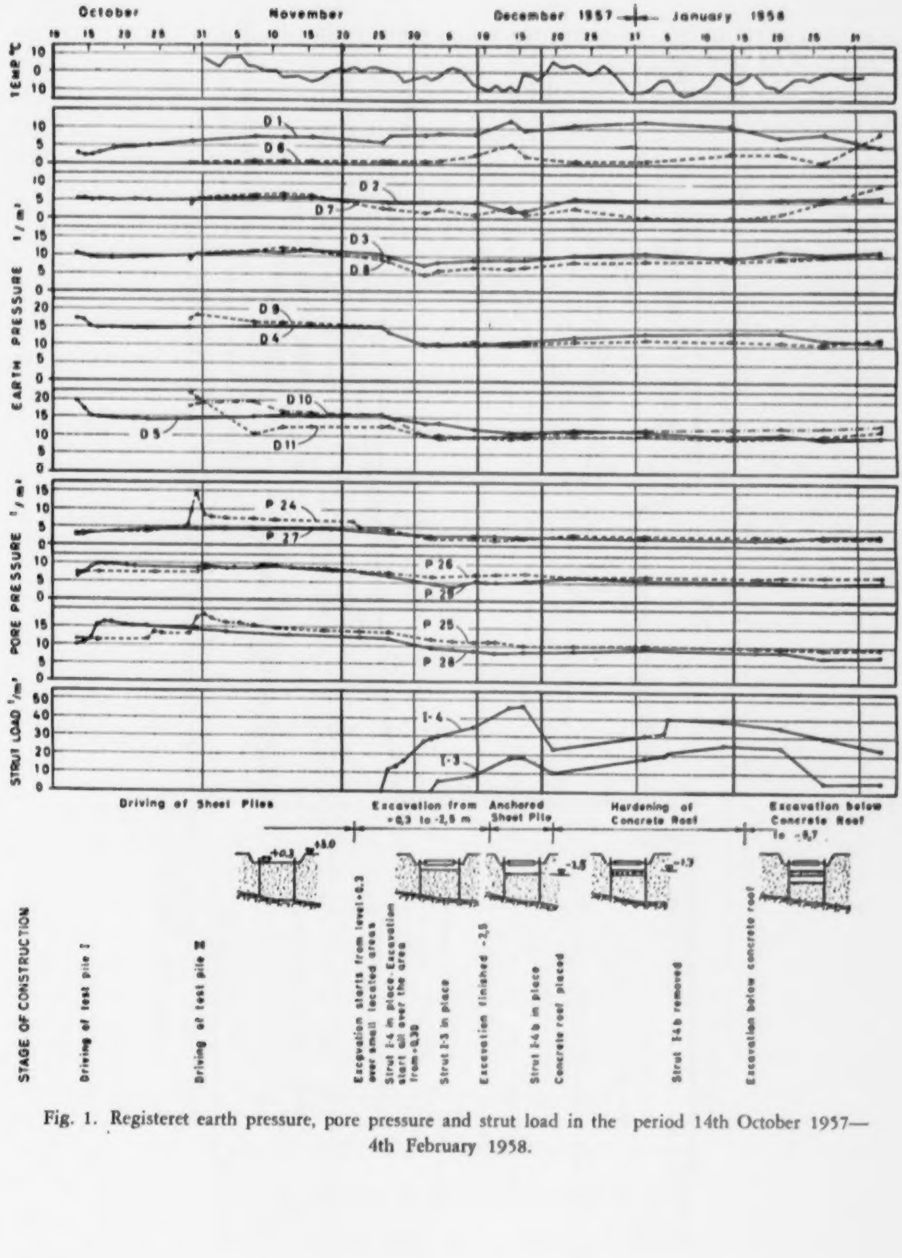

Fig. 1. Registeret earth pressure, pore pressure and strut load in the period 14th October 1957—4th February 1958.

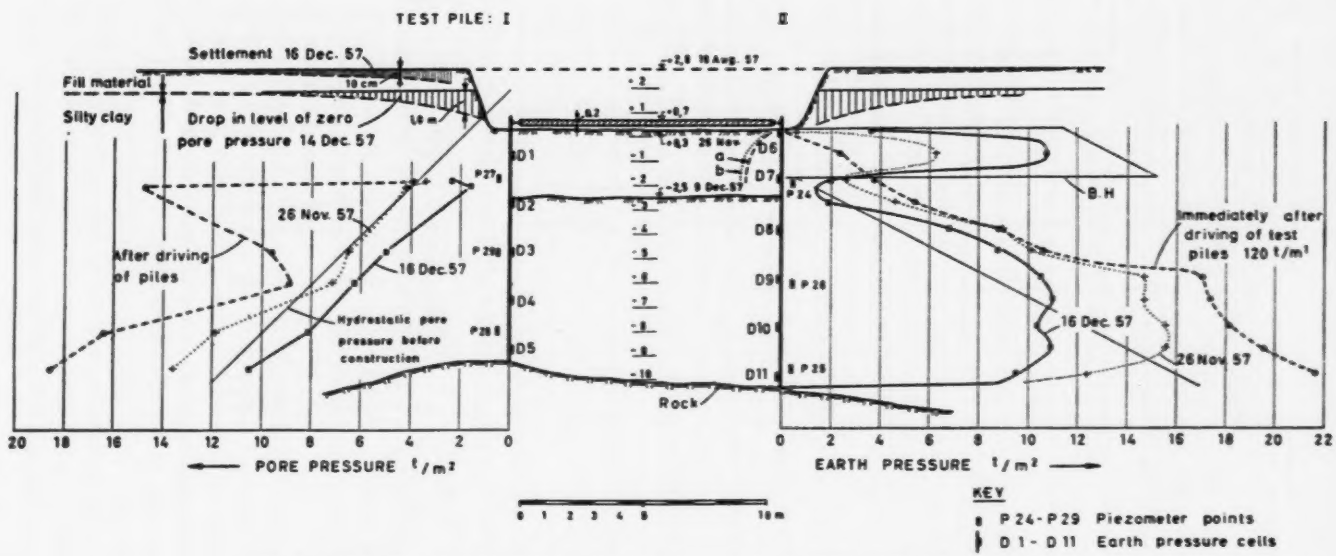

Fig. 2. Distribution of earth pressure and pore pressure for a single strutted (anchored) sheet piling. 16th December 1957.

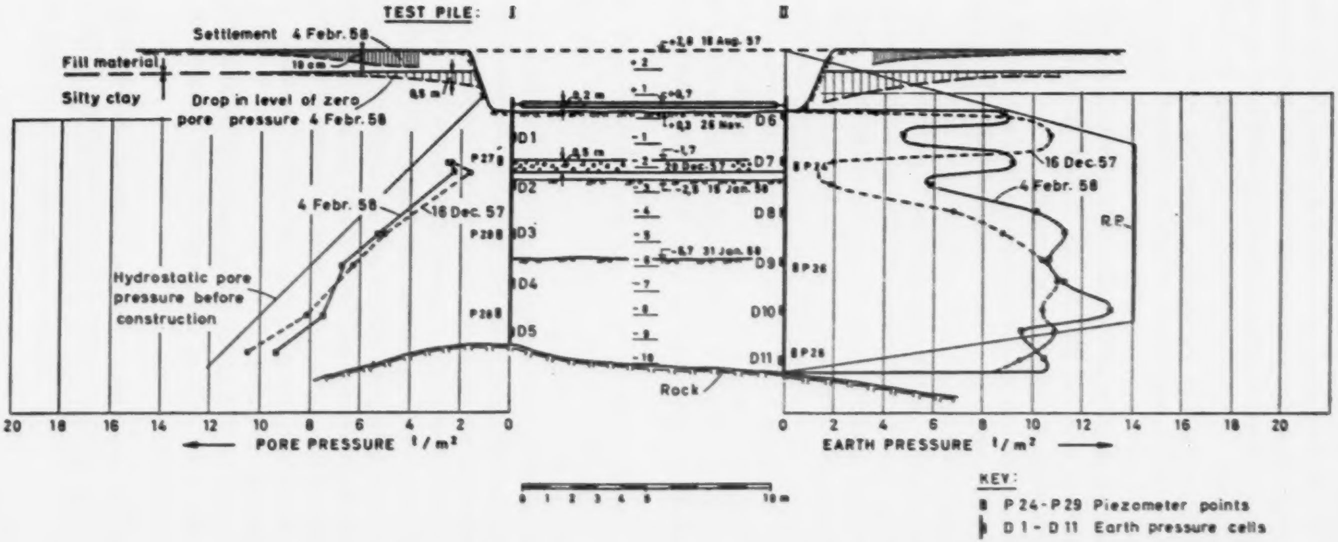

Fig. 3. Distribution of earth pressure and pore pressure on a double strutted sheet piling.
4th February 1958.

As representative for the stage of construction when the level of excavation is -2,5 and the sheet pile strutted only at level approximately + 0,6, the earth pressure registered on the 16th of December is given on Fig. 2. The plotted values of earth pressure at the level of the three upper cells are taken as an average of readings on the 13th and 16th of December. The three upper cells are situated above the excavated level and are therefore exposed to changes in temperature which to a certain degree influences the readings.1)

In spite of the small error involved (possibly $\pm$ 1 t/m^2) in interpreting the earth pressure acting at the sheet pile, the general trend of earth pressure distribution shown for this stage of construction is thought to be correct.

The earth pressure calculated in accordance with the theory of Brinch Hansen for an anchored sheet pile is also given in Fig. 2, and is marked with B.H. As may by seen, the meassured and calculated earth pressures are in fairly good agreement.

As a check on the reliability of the measured earth pressure, the curves marked a and b in Fig. 2 show the bending moments in the sheet piles calculated in the following ways. Firstly, the bending moments in the sheet pile, acting as an anchored wall, that is strutted at level + 0,6, and excavation to -2,5, is calculated on the basis of the measured stresses in the test pile, curve a. Secondly, the bending moment in the pile above the excavated level is calculated based on the measured earth pressures and strut loads, curve b. The strut loads per running meter of wall are determined from the measurements in two struts as given in Fig. 1. As may be seen, both ways of calculating the bending moments lead to approximately the same result, indicating the reliability of the measurements.

Fig. 3 shows, in a similar manner to Fig. 2, the distribution of earth pressure registered on the fourth of February, 1958. The sheet pile is strutted at approximately levels +0,6 and -2,0, the excavated level being at -5,7.

The earth pressure distribution given by the curve marked February 4th, 1958, is characterized by its peaks concentrated with their maximum values at the levels of the upper two struts. Below the tvo struts, the earth pressure is found to have increased compared with the pressure coresponding to the single strutted pile at the 16th December, 1957. It should, however, be noted that this development of pressures below the lower strut mainly occured before the excavation from level -2,5 started and, therefore, is due to the load applied at the excavated level -2,5 by placing the concrete roof, which forms the second strut. The maximum earth pressure registered at the cells below the second strut in the period after the concreting and before excavation from level -2,5 is shown by crosses in Fig. 3.

The earth pressure given by R. Peck for calculating the strut loads is marked by R.P., and encloses partly the upper limit of the registered earth pressure, calculated for the full height above rock surface.

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1) Tests in the laboratory have shown that a temperature gradient through the cell corresponding to 10° C difference in temperature results in an error of registered earth pressure of approximately 0,7 t/m^2. (Øyen, 1958).

Table 1 gives the total measured earth pressure per running meter of the wall for some of the earth pressure distributions shown by the curves in Figs. 2 and 3. Furthermore, the active earth pressure

$$P_A = {}^1/_2\,\gamma H^2 - 2c\sqrt{1 + \frac{c_o}{c}} \cdot H,$$

is calculated, taking undrained shear strength equal to 2,5 t/m², bulk density equal to 1,9 t/m,³ (Johannessen 1958), H — 13,1 m, and no surcharge on the ground.

TABLE I

Active earth pressure	c_o/c — 0	97,5 t/m
	c_o/c — 1.0	70,5 t/m
Pressure on 16th Décember 1957		86,0 t/m
Pressure on 4th February 1958		98,0 t/m
After Brinch Hansen		98,0 t/m
After Ralph Peck		151,0 t/m
Immediatly after driving		120,0 t/m

The table shows that the total earth pressure per running meter of the wall, calculated by means of classical theory is in good agreement with the total measured pressure.

3. CONCLUSIONS

The results of the tests described in this paper lead to the following conclusions:

The earth pressure on a strutted sheet pile in clay is not distributed according to the classical theory of earth pressure, the total pressure per running meter of the wall, however, is in accordance with the classical theory.

The distribution of earth pressure necessary for the design of the single strutted sheet pile could have been estimated by means of the theory of J. Brinch Hansen.

The empirical diagram given by R. Peck (for the full height of sheet piling) seems to enclose the maximum earth pressure registered for the different stages of canstruction concerned.

Further measurements must be obtained before the above mentioned conclusions can be concidered generally applicable.

4. ACKNOWLEDGEMENT

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Messrs. A. Angvik, I. Johannessen and K. Øyen have made valuable contributions to the tests described, for which the author is very grateful.

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APPENDIX

(Contribution by B. Kjærnsli to the discussion on his paper.)

Referring to the above paper, the author wishes to make a few supplementary remarks on results obtained after the paper was written from tests carried out at the excavation for the Oslo Subway. The excavation concerned is carried out between strutted sheet piles in soft clay.

From the conclusion of the above mentioned paper the following is reread:

«The earth pressure on a strutted sheet pile is not distributed according to classical theory of earth pressure, the total pressure per running metre of wall, however, is in accordance with the classical theory.»

The above given conclusion seems only partly to be correct, as the measured earth pressure on the wall does increase with increasing number of struts placed in the excavation. This tendency is already shown in table 1 of the above paper. The earth pres-

sure for a single strutted wall, December 16th, 1957, being 86,0 t/m, and for a double strutted wall, February 4th, 1958, being 98,0 t/m. By three struts in depth the earth pressure has further been measured as high as approximately 120 t/m.

Calculating the active earth pressure as

$$P_A = \frac{1}{2}\gamma H^2 - 2cH\left(1+\frac{c_o}{c}\right)+\frac{2c^2}{\gamma}\left(1+\frac{c_o}{c}\right)$$

that is neglecting the negative pressure, and taking c, p, H as given in the above mentioned paper, P_A is 104 and 80 t/m for c_o/c equal to 0 resp. 1,0. As the sheet piles are founded on rock, the last value of pressure is taken as the theoretical calculated earth pressure: P_A — 80 t/m.

The ratio of the measured to the calculated pressure is for the sheet pile strutted by one, two and three struts, 1.1, 1.2 and 1.5 respectively.

The conclusion based on the results of test carried out is therefore that neither the distribution nor the total thrust of earth pressure may be calculated in accordance with classical theory of earth pressure.

Further measurements must be obtained before the above mentioned conclusions can be considered as generally applicable.

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